Skyglow extends into the world's Key Biodiversity Areas

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Abstract

The proportion of the Earth's surface that experiences a naturally dark environment at night is rapidly declining with the introduction of artificial light. Biological impacts of this change have been documented from genes to ecosystems, and for a wide diversity of environments and organisms. The likely severity of these impacts depends heavily on the relationship between the distribution of artificial nighttime lighting and biodiversity. Here, we carry out a global assessment of the overlap between areas of conservation priority and the most recent atlas of artificial skyglow. We show that of the world's Key Biodiversity Areas (KBAs), less than a third have completely pristine nighttime skies, about a half lie entirely under artificially bright skies, and only about a fifth contain no area in which nighttime skies are not polluted to the zenith. The extent of light pollution of KBAs varies by region, affecting the greatest proportion of KBAs in Europe and the Middle East. Statistical modelling revealed associations between light pollution within KBAs and associated levels of both gross domestic product and human population density. This suggests that these patterns will worsen with continued economic development and growth in the human population.

Keywords: Artificial lighting, Atmosphere, Biodiversity, Nighttime, Streetlights

Introduction

The erosion of the nighttime through the introduction of artificial lighting, from street-lighting and other sources, has pervasive environmental impacts. These span changes in the physiology and behaviour of individual organisms, in the abundance and distribution of species, in the structure and functioning of ecological communities, and in the provision of ecosystem services (Gaston *et al*., 2013, 2014). A wide diversity of terrestrial, freshwater and marine organisms is influenced, including microbes, plants and many groups of animals (e.g. crustaceans, molluscs, insects, fish, amphibians, reptiles, birds, mammals; Gaston *et al*., 2013; Bennie *et al*., 2016).

To date, attention has focussed foremost on the environmental impacts of the direct emissions from sources of nighttime lighting. This is, however, only relatively narrowly spatially distributed compared with the skyglow that is caused by upwardly emitted or reflected artificial light being scattered in the atmosphere by water, dust and gas molecules. The latter has been estimated already to extend over ~23% of the global land area (Falchi *et al*., 2016). It can increase background sky brightness to levels comparable to those of late twilight and moonlight, and can obscure the visibility to humans of individual stars and the Milky Way (83% of the human population lives under light polluted skies; Falchi *et al*., 2016). It is likely to interfere with multiple biological processes including activity patterns of diurnal, crepuscular and nocturnal species (which are variously sensitive to timing of twilight and nighttime levels of moonlight; e.g. Moore *et al*., 2000; Bachleitner *et al*., 2007), and nighttime orientation and navigation (which often involves the use of stars and other celestial objects; e.g. Foster *et al*., 2017). Some free-living organisms are able to detect and respond to extraordinarily low levels of nighttime light (e.g., Warrant *et al*., 2004).

Particularly because of the contribution of light that is emitted, or reflected, at relatively shallow angles to the horizontal, skyglow can extend substantial distances (up to hundreds of kilometers) from urban sources of nighttime lighting (Luginbuhl *et al*., 2014). This raises the potential for impacts of artificial nighttime lighting to reach many globally important biodiversity areas, even when these are reasonably remote from many other anthropogenic pressures. In this paper, we estimate the extent of this overlap, based on the most recent global modelling of skyglow and the distribution of Key Biodiversity Areas (KBAs).

Materials and methods

Data

Estimates of global variation in skyglow were obtained from Falchi *et al*. (2016). This surface was produced by the modelling of measured upward radiance from artificial sources from satellite imagery (from the VIIRS DNB sensor on the Suomi National Polar-orbiting Partnership (NPP) satellite), and ground measurements. The data are presented for the entire area (terrestrial and marine) between approximately 85°N and 60°S, at a spatial resolution of 30-arcseconds (~1 km) as a ratio of artificial brightness to natural brightness (typical night sky background excluding the brightest stars and the Milky Way). The authors define the level of artificial brightness under which a sky can be considered "pristine" as up to 1% above the natural background level (ratio of 0.01). At a level of 8% or more above natural conditions (ratio of 0.08) light pollution extends from the horizon to the zenith and the entire sky can be considered polluted. We use these two thresholds in our analysis.

Key Biodiversity Areas (KBAs) are sites that contribute significantly to the global persistence of biodiversity, and use quantitative criteria to identify places that support viable populations of species for which site-scale conservation is appropriate (IUCN, 2016). The current inventory includes Important Bird and Biodiversity Areas (IBAs), KBAs identified during Biodiversity Hotspot profiles supported by the Critical Ecosystem Partnership Fund (CEPF) and Alliance for Zero Extinction sites (AZEs) (http://www.keybiodiversityareas.org/home). We used boundary data (BirdLife International, 2016) for all 14,979 KBAs for which polygons were available in December 2016 (comprising >95% of all KBAs recognised in March 2018). Only those that lie within the extent of the skyglow data were considered further (14,765). These had a combined coverage of 34,785,579 sq km, with a median area of 209 sq km (calculated in ArcGIS 10.3.1, ESRI Inc.; WGS84 datum). The KBA dataset includes characterisation by region, and this includes a "Marine" category identifying those which are predominantly marine based.

Data were also obtained on three further variables that are of potential significance as determinants of the levels of skyglow experienced by KBAs (excluding those on the 'High seas'): Gross Domestic Product (GDP; which provides a measure of economic activity), human population density, and protected area coverage: (i) Median GDP per capita, adjusted for purchasing power parity (PPP), was extracted from the gridded (spatial resolution of 5 arc-min) product by Kummu *et al.* (2018). GDP grid cells were included in the median calculation if the centre was within the KBA boundary (missing n = 792; 95 % of KBAs retained for further analysis). This product uses sub-national datasets where possible in combination with national datasets (including the World Bank Development Indicators database and the CIA World Factbook for missing data). (ii) Median human population density for each KBA was extracted from the gridded population density data (resolution of ~1 km) of the world projected for the year 2015 from census data (CIESIN, 2016) where data were included when the centre of the grid cell was located inside the KBA boundary (missing n = 291). And, (iii) protected area coverage for each KBA was calculated using the World Database of Protected Areas (IUCN and UNEP-WCMC, 2016). Protected areas were only included where they had associated spatial boundary data.

Data analysis

Analyses were carried out in the software package R (version 3.1.3) (R Development Core Team, 2014) using the packages "raster" (version 2.5.2) and "rgdal" (version 1.1.8). Ratio values of artificial sky brightness were extracted from the global dataset for each KBA. Sky brightness values were stored as a grid (raster) with a spatial resolution of 30-arcseconds (~1 km). Values were included when the centre of the corresponding cell was located within the KBA boundary. Two measures were calculated for each KBA: (i) percentage coverage by pristine nighttime skies (ratio values of ≤0.01) and (ii) percentage coverage by skies not polluted from the horizon to zenith (ratio values <0.08). In addition, we calculated the percentage coverage of the total area of KBAs by these respective levels of sky brightness.

The percentiles (0 - 100) were calculated for both the median KBA GDP (per capita, PPP, thousand $) and median KBA population density (people per sq km). The median proportion pristine for the KBAs with each combination of GDP and population density percentile was then calculated and plotted. The use of percentiles maximises the evenness of the sample sizes for each combination.

We used a generalised linear model (GLM), with a binomial error structure and logit link function to model whether a KBA had entirely pristine skies or not as a function of GDP per capita, population density, the interaction between the two, and the proportion of the KBA that falls within a protected area. To account for strong right skew in population density, population density was categorised on a log scale (0 - 1 people per sq km, >1 - 10, >10 - 100, >100 - 1,000 and >1,000). Proportion protected had a bimodal distribution with high proportions of KBAs either fully or not protected at all. This variable was dichotomised as either fully protected (100 % protected) or not (<100 % protected). Model fit is given by McFadden's *pseudo*-R^2. Although there was significant pair-wise correlation between the predictor variables, the generalised variance inflation factors, standardised by degrees of freedom, were all <2 (Supp. Tables 1-2).

Results

A half (51.5%) of the total number of KBAs assessed contained no area with pristine nighttime skies while less than one third (29.5%) had completely pristine nighttime skies (ratio values ≤0.01 ≈ up to 1 % above natural conditions; Fig. 1a). Europe had the greatest percentage (81%) of KBAs containing no area of pristine skies, followed by the Middle East (75%) and the Caribbean (64%; Fig. 2a). The only regions in which all KBAs had completely pristine skies were Antarctica and Marine (Fig. 2a).

About one fifth (21.0%) of all KBAs consisted entirely of area in which night skies were polluted to the zenith (Fig. 1b). However, over a half of KBAs (51.9%) are completely free of skies polluted to the zenith (ratio values <0.08 ≈ up to 8 % above natural conditions; Fig. 1b). The Middle East was the region where the greatest percentage (46 %) of KBAs had nighttime skies entirely polluted to the zenith, followed by Europe (34%) and the Caribbean (32%; Fig. 2).

Of the summed global area of KBAs, more than 15% was not pristine and more than 5% was polluted to the zenith (Fig. 2b). The Middle East was the region with the greatest percentage (54%) of the overall KBA area not having pristine skies, followed by Europe (53%) and the Caribbean (33%; Fig. 2b). These were also regions with the largest percentage of the overall KBA area that is polluted to the zenith (Middle East - 25%, Europe - 19%, Caribbean - 10%; Fig. 2b).

The likelihood of a KBA having pristine skies decreased with increasing GDP and population density, and the interaction between the two, and increased with proportional coverage by protected areas (Table 1). Neither the categories 1 - 10 people per sq km or 10 - 100 people per sq km were found to be significantly different to 0 - <1 people per sq km. Where there were >100 to 1,000 people per sq km, KBAs were less than half as likely to be pristine (compared to 0 - <1 people per sq km; Odds ratio (OR) = 0.44, 95 % Confidence interval (CI) = 0.34 - 0.56). Where there were >1,000 people per sq km, the likelihood that the KBA would be entirely pristine was extremely low (OR = 0.02, 95 % CI = 0.01 – 0.06). With every increase in GDP by $1,000 there was an associated decrease in likelihood of being pristine by ~1 % (OR = 0.99, 95 % CI 0.98 - 0.99). KBAs which were fully protected were 1.2 x as likely to be pristine compared to those not fully protected (OR = 1.24, 95 % CI = 1.05 - 1.7). There was also a significant interaction between population density and GDP (Table 1; Fig. 3).

Discussion

Skyglow is often envisaged as an exclusively urban issue. However, both modelling and ground measurements have shown it to be very widespread, often being propagated over long distances from sources (Kyba *et al*., 2015; Falchi *et al*., 2016). Nevertheless, it is perhaps surprising that less than a third of KBAs had completely pristine nighttime skies, more than a half contained no area with pristine skies, and that a sixth of the total area of KBAs was light polluted. This is especially so considering that the global data on skyglow are likely, if anything, to be conservative estimates of its extent. Such data are primarily estimated using satellite measurements and, as such, are for 'open sky' conditions (cloud-free). They therefore do not take into account the amplification of skyglow that can occur by cloud cover (Jechow *et al.*, 2017), and likely under-represent the occurrence of artificial brightness of horizons (which may be important for many organisms, for example in influencing predator-prey interactions).

These results are especially troubling because it has become increasingly apparent that organisms can respond even to absolutely small (which may nonetheless be relatively large) changes in natural nighttime light conditions (Warrant *et al*., 2004), in perceived day lengths (Gaston *et al*., 2017), and in artificial nighttime lighting (Gaston *et al*., 2014). The breadth and number of species whose behaviour is influenced by skyglow seems likely to be large.

Unsurprisingly, the likelihood of the skies of a KBA experiencing skyglow tends to increase in countries with higher GDP, and in areas with higher human population density, consistent with global results (Gallaway, Olsen & Mitchell, 2010). It is possible to have KBAs in regions with relatively pristine skies in areas with high human densities when these populations are economically poor, and likewise in areas with high GDP when these populations are at low density (Fig. 4). However, under virtually all other circumstances KBAs exist under light polluted skies. This strongly suggests that globally the proportion of KBAs experiencing skyglow will almost certainly increase in parallel with developing country economies.

The relatively small areal extent of many KBAs means that most commonly their skies are either entirely light polluted or entirely unpolluted. Whether they have coverage by protected areas is also associated with whether they experience skyglow, consistent with results for upwardly emitted light (Gaston, Duffy & Bennie, 2015). However, this seems in most cases unlikely to be a consequence of protection *per se*. More likely, it is a result of the tendency for protected areas to be distributed away from urban centres (and hence sources of artificial light), and often in regions with reduced competition over land use (Gaston *et al*., 2008).

Here we have identified the regions where KBAs are most affected by skyglow. This effectively prioritises areas for further detailed assessment of the potential risk to species of conservation priority inhabiting these. To assess the risk, the extent of overlap between skyglow and species ranges and occupancy could be calculated. A similar technique has been applied to cacti and mammal species ranges, where the overlap with light pollution was calculated for upwardly emitted light radiation measured directly from satellites (Duffy *et al*., 2015; Correa-Cano *et al*., 2018). Further research could also identify areas currently minimally affected by light pollution but at risk of increases in future due to rapidly developing economies or with increasing populations, facilitating the development of mitigation measures in these areas.

Dramatic reductions in anthropogenic pressures on biodiversity are often costly to achieve, and there are commonly substantial lag times between such reductions and biodiversity responses. By contrast, marked reductions in skyglow could be achieved by limiting outdoor artificial lighting to levels and places where it is required by people, which would result in considerable cost savings without undermining the benefits that it brings. Indeed, one might argue that environmental benefits and financial savings from considered lighting policies are closely aligned (Gaston, 2013).

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References

Bachleitner, W., Kempinger, L., Wülbeck, C., Rieger, D. & Helfrich-Förster, C. (2007). Moonlight shifts the endogenous clock of *Drosophila melanogaster*. *Proc. Natl Acad. Sci*, *USA*. **104**, 3538-3543.

Bennie, J., Davies, T.W., Cruse, D. & Gaston, K.J. (2016). Ecological effects of artificial light at night on wild plants. *J. Ecol*. **104**, 611-620.

BirdLife International. (2016). KbaMapGlobal_2016_03. Accessed on: 2nd December 2016

CIESIN. (2016). Gridded Population of the World, Version 4 (GPWv4): Population Density 2015. (ed. Center for International Earth Science Information Network - CIESIN - Columbia University). NASA Socioeconomic Data and Applications Center (SEDAC), Palisades, NY. http://dx.doi.org/10.7927/H4F47M2C

Correa-Cano, M.E., Goettsch, B., Duffy, J.P., Bennie, J., Inger, R. & Gaston, K.J. (2018). Erosion of natural darkness in the geographic ranges of cacti. *Sci. Rep*. **8**, 4347.

Duffy, J.P., Bennie, J., Duran, A.P. & Gaston, K.J. (2015). Mammalian ranges are experiencing erosion of natural darkness. *Sci. Rep.* **5**, 6.

Falchi, F., Cinzano, P., Duriscoe, D., Kyba, C.C.M., Elvidge, C.D., Baugh, K., Portnov, B.A., Rybnikova, N.A. & Furgoni, R. (2016). The new world atlas of artificial night sky brightness. *Sci. Adv*. **2**, e1600377.

Foster, J.J., Jundi el, B., Smolka, J., Khaldy, L., Nilsson, D-E., Byrne, M.J. & Dacke, M. (2017). Stellar performance: mechanisms underlying Milky Way orientation in dung beetles. *Phil. Trans. R. Soc. Lond. B* **372**, 20160079.

Gallaway, T., Olsen, R.N. & Mitchell, D.M. (2010). The economics of global light pollution. *Ecol. Econ*. **69**, 658-665.

Gaston, K.J. (2013). A green light for efficiency. *Nature* **497**, 560-561.

Gaston, K.J., Bennie, J., Davies, T.W. & Hopkins, J. (2013). The ecological impacts of nighttime light pollution: a mechanistic appraisal. *Biol. Rev*. **88**, 912-927.

Gaston, K.J., Davies, T.W., Nedelec, S.L. & Holt, L.A. (2017). Impacts of artificial light at night on biological timings. *Annu. Rev. Ecol. Evol. Syst*. **48**, 49-68.

Gaston, K.J., Duffy, J.P., Gaston, S., Bennie, J. & Davies, T.W. (2014). Human alteration of natural light cycles: causes and ecological consequences. *Oecologia* **176**, 917-931.

Gaston, K.J., Duffy, J.P. & Bennie, J. (2015). Quantifying the erosion of natural darkness in the global protected area system. *Conserv. Biol.* **29**, 1132-1141.

Gaston, K.J., Jackson, S.F., Cantú-Salazar, L. & Cruz-Piñón, G. (2008). The ecological performance of protected areas. *Annu. Rev. Ecol. Evol. Syst.* **39**, 93-113.

IUCN. (2016). A Global Standard for the Identification of Key Biodiversity Areas, Version 1.0. First edition. IUCN, Gland, Switzerland.

IUCN and UNEP-WCMC. (2016). The World Database on Protected Areas (WDPA) December 2016. UNEP-WCMC, Cambridge, UK.

Jechow, A., Kollath, Z., Ribas, S.J., Spoelstra, H., Holker, F. & Kyba, C.C.M. (2017). Imaging and mapping the impact of clouds on skyglow with all-sky photometry. *Sci. Rep*. **7**, 10.

Kummu, M., Taka, M. & Guillaume, J.H.A. (2018). Gridded global datasets for Gross Domestic Product and Human Development Index over 1990–2015. *Sci. Data*, **5,** 180004.

Kyba, C.C.M., Tong, K.P., Bennie, J., Birriel, I., Birriel, J.J., Cool, A., Danielsen, A., Davies, T.W., den Outer, P., Edwards, W., Ehlert, R., Falchi, F., Fischer, J., Giacomelli, A., Giubbilini, F., Haaima, M., Hesse, C., Heygster, G., Hölker, F., Inger, R., Jensen, L.J., Kuechly, H.U., Kuehn, J., Langill, P., Lolkema, D.E., Nagy, M., Nievas, M., Ochi, N., Popow, E., Posch, T., Puschnig, J., Ruhtz, T., Schmidt, W., Schwarz, R., Schwope, A., Spoelstra, H., Tekatch, A., Trueblood, M., Walker, C.E., Weber, M., Welch, D.L., Zamorano, J. & Gaston, K.J. (2015). Worldwide variations in artificial skyglow. *Sci. Rep*. **5**, 8409.

Luginbuhl, C.B., Boley, P.A. & Davis D.R. (2014). The impact of light source spectral power distribution on sky glow. *J. Quant. Spect. Rad. Trans*. **139**, 21-26.

Moore, M., Pierce, S., Walsh, H., Kvalvik, S. & Lim, J. (2000). Urban light pollution alters the diel vertical migration of *Daphnia*. Intern. Verein. *Theor. Ang. Limnol*. Ver. **27**, 779-782.

R Development Core Team. (2014). R: A language and environment for statistical computing. R Foundation for Statistical Computing. ISBN 3-9 00051-07-0, Vienna, Austria http://www.R-project.org.

Warrant, E.J., Kelber, A., Gislén, A., Greiner, B., Ribi, W. & Wcislo, W.T. (2004). Nocturnal vision and landmark orientation in a tropical halictid bee. *Curr. Biol*. **14**, 1309-1318.

World Bank. (2016). GDP per capita, PPP (current international $). Available at: http://data.worldbank.org/indicator/NY.GDP.PCAP.PP.CD Accessed 27th February 2017

Table 1

Results of GLM (binomial) of relationship between whether a Key Biodiversity Area had entirely pristine skies or not and per capita GDP (median within KBA), human population density, the interaction between the two, and the proportion of the KBA that falls within a protected area.

Variable	Estimate	Standard error	Z value	*p*	OR	95 % CI
Population density (people per sq km)						
> 1,000	-3.82	0.52	-7.42	<0.001	0.02	0.01 - 0.06
>100 - 1,000	-0.83	0.13	-6.37	<0.001	0.44	0.34 - 0.56
>10 - 100	0.15	0.11	1.40	0.161	1.16	0.94 - 1.44
>1 - 10	0.22	0.12	1.88	0.060	1.25	0.99 - 1.58
0 - 1 (ref)						
Median GDP (thousands)	-0.01	0.00	-3.73	<0.001	0.99	0.98 - 0.99
Proportion protected						
100 %	0.22	0.09	2.51	0.012	1.24	1.05 - 1.47
<100 % (ref)						
Interaction population density x GDP						
*> 1,000 * GDP*	-0.04	0.04	-0.95	0.341	0.96	0.88 - 1.04
*>100 – 1000 * GDP*	-0.33	0.03	-10.83	<0.001	0.72	0.68 - 0.76
*>10 – 100 * GDP*	-0.24	0.01	-24.92	<0.001	0.79	0.77 - 0.80
*>1 – 10 * GDP*	-0.09	0.01	-13.82	<0.001	0.92	0.91 - 0.93
*0 - 1 (ref) * GDP*						
Intercept	0.47					
N	13913					
McFadden's *pseudo*-R^2	0.27					

OR = odds ratio

95 % CI = 95 % Confidence Interval

Fig. 1. The proportion of the extent of Key Biodiversity Areas with a) pristine nighttime skies (ratio of artificial brightness to natural brightness ≤0.01) and b) nighttime skies not polluted to the zenith (ratio of artificial brightness to natural brightness <0.08). The outlines have been exaggerated for display purposes.

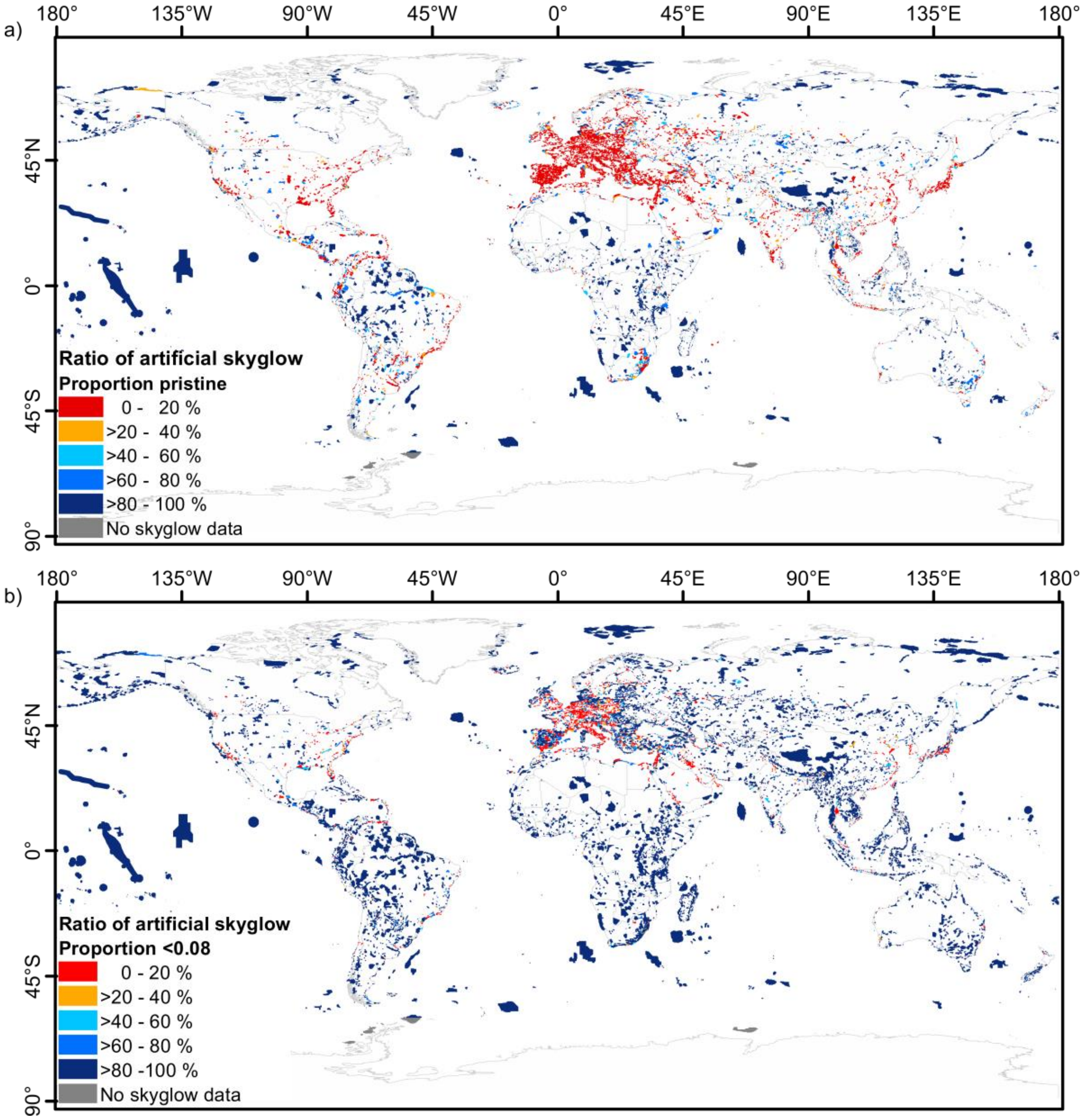

Fig. 2. a) Proportion of Key Biodiversity Areas which have 0% and 100% coverage of pristine nighttime skies (ratio threshold of artificial brightness to natural brightness ≤0.01) and skies not polluted to the zenith (ratio threshold of artificial brightness to natural brightness <0.08). b) Total proportion of area with pristine night time skies and skies not polluted to the zenith (ratio of artificial brightness to natural brightness <0.08) (bottom). Skyglow ratio thresholds are specified on the χ axis. Regions displayed in alphabetical order, the marine region is excluded as it is 100 % pristine.

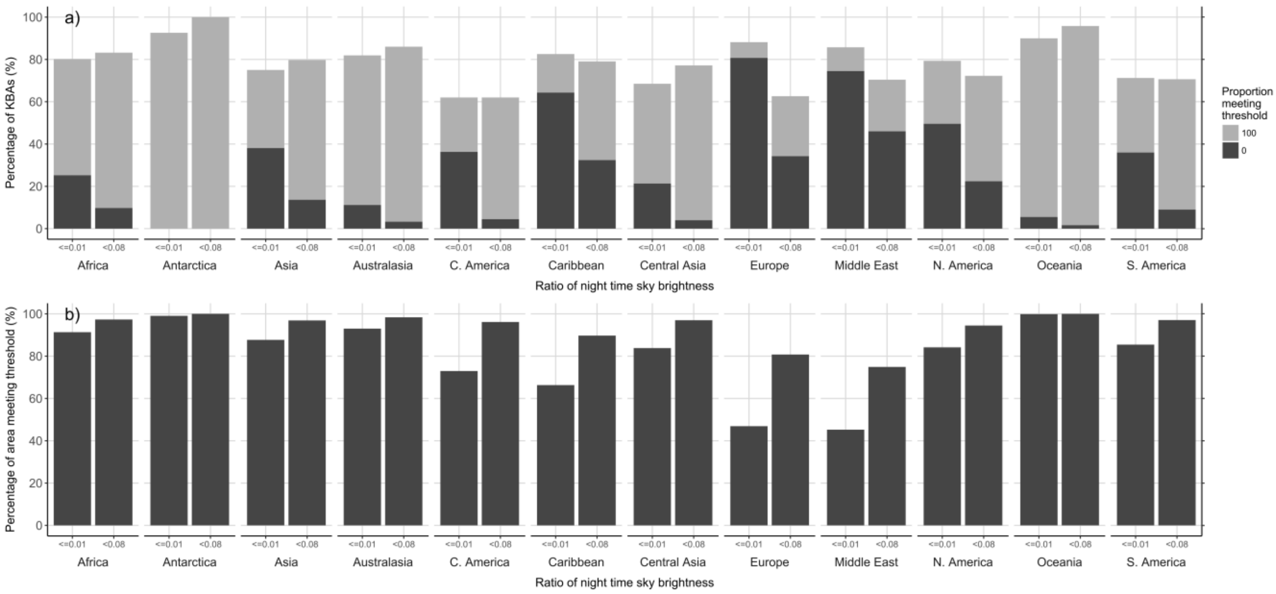

Fig. 3. Predicted probabilities of KBA being pristine from GLM model results as a function of GDP and population density, and fixed proportion protected of 100 %. Note the interaction between population density of >1,000 and GDP was not significant.

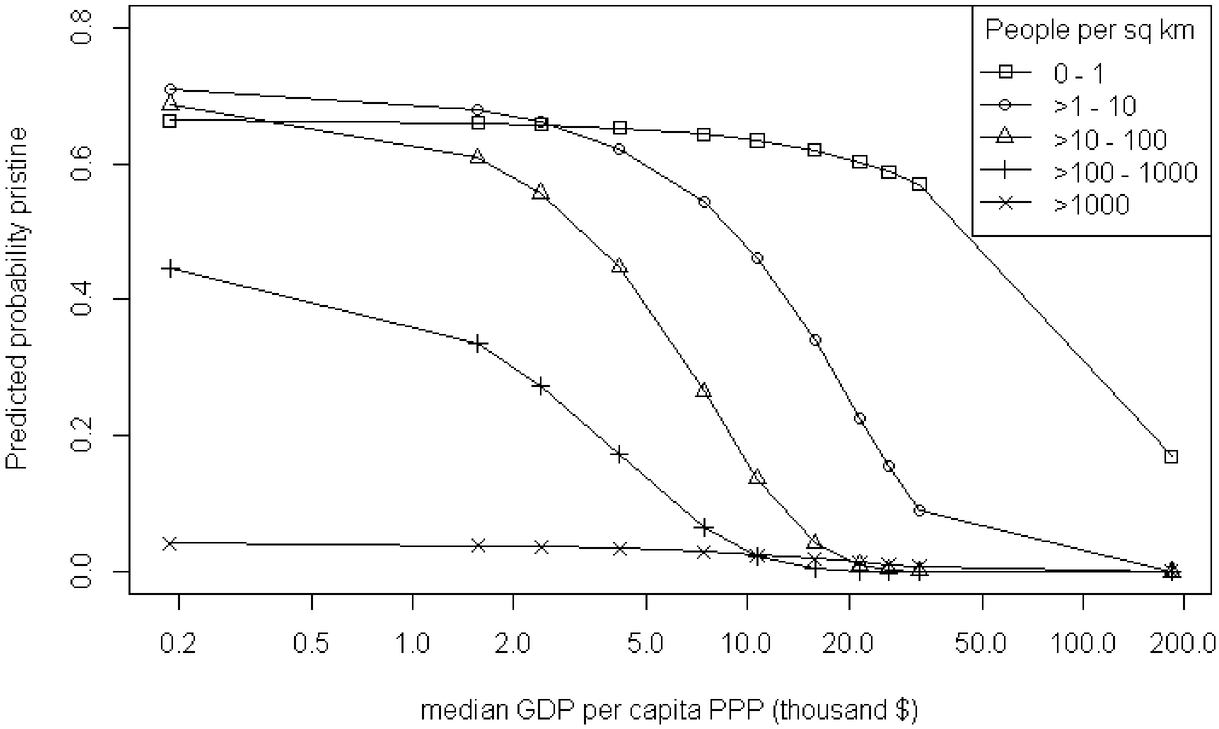

Fig. 4. Median proportion of Key Biodiversity Areas that has pristine nighttime skies for each combination of GDP and population percentile (0-100).